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RESPIRATORY HEAT EXCHANGE WITH VARYING TEMPERATURE AND HUMIDITY OF INSPIRED AIR

20030917000

University of California

United States Air Force
Air Materiel Command
Wright-Patterson Air Force Base, Dayton, Ohio

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RESPIRATORY HEAT EXCHANGE WITH VARYING TEMPERATURE AND HUMIDITY OF INSPIRED AIR

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FOREWORD

The research reported herein was carried out in the laboratories of the Department of Engineering, University of California, Los Angeles, in part, under contract #33-038 ac-14504. This contract is sponsored by the Aero Medical Laboratory, Air Materiel Command.

The present investigation was performed by Mr. McCutchan as a research problem toward the Master of Science degree in Engineering, with Dr. Taylor as advisor. The present form of the report is a product of their collaboration. Personnel of the Human Heat Tolerance Project and the facilities of that project were used in the experimental work.

The authors gratefully acknowledge the aid of W.V. Blockley, E.R. Hallett, L. Doshay, and G.L. Tingley who served as subjects.

We also acknowledge the cooperation of L.M.K. Boelter, chairman of the department; and Robert Bromberg, technical representative of the chairman.

PUBLICATION REVIEW

Manuscript Copy of this report has been reviewed and found satisfactory for publication.

FOR THE COMMANDING GENERAL:

Walter A. Carlson
WALTER A. CARLSON
Colonel, USAF (MC)
Chief, Aero Medical Laboratory
Engineering Division

ABSTRACT

Respiratory heat exchange has been measured by determinations of temperature, humidity and mass flow of inspired and expired airs. The ranges of inspired temperatures and humidities were 80 to 180°F and 0.2 to 1.2 in. Hg vapor pressure resp. Five normal young men served as subjects in 61 experiments.

Specific enthalpy difference between inspired and expired airs proved to be the most fundamental heat quantity: (a) as judged by satisfactory predictive relationships which are independent of rate and volume of respiration, (b) as established by satisfactory theoretical accountings for the heat and mass transfer process. By setting specific enthalpy difference equal to zero it was found that inspired and expired wet bulb temperatures agreed very closely. This permits the interpretation that adiabatic sensible and latent heat exchanges, between inspired and expired air, take place at constant total heat.

Predictive equations have been developed for specific enthalpy difference (Btu / lb), as follows:

$$\Delta H = 0.191\ t_i + 810\ W_i - 48.37\ ; \qquad SE_{est} = \pm 2.01$$

$$\Delta H = 0.0105\ t_w^2 - 0.833\ t_w - 15.81\ ; \qquad SE_{est} = \pm 1.59\ .$$

where

t_i = temperature of inspired air (°F)

t_w = wet bulb temperature of inspired air (°F)

W_i = humidity of inspired air (lb / lb)

The temperature, humidity and enthalpy properties of expired air are described mathematically and graphically. Discussion of these results with other investigations in the literature, where comparison is justified, reveals satisfactory agreement when states of unsaturation of the expired air are considered.

INTRODUCTION

In the course of studies on human exposures to air temperatures ranging up to 240°F (115.5°C) and humidities ranging up to 1.4 in. Hg (35.6 mm) vapor pressure, the possibility of intolerable heating of the respiratory passages or lungs as a limiting factor had continuously been entertained. Actually under the conditions of the experiments this fear was not realized, and all symptoms specifically referable to the respiratory tract proved to be mild and without important effect upon the duration of the experiment. It became clear that, like sweat evaporation in its effect upon the skin, the evaporative cooling mechanism of the respiratory tract has great capacity to absorb sensible heat through humidification.

A few preliminary measurements made in 1948[2] showed that ambient air at 220°F typically took the following temperature course:

Measurement		Oral Breathing	Nasal Breathing
Inhalation:	At portal of nose or mouth,	190°F	188°F
	1.5 in. within nose or mouth,	135°F	110°F
Exhalation:	1.5 in. within nose or mouth,	104°F	102°F
	At portal of nose or mouth,	110°F	114°F

These results clearly show the rapid reduction in temperature even with short traverse within the respiratory tract: and, in part, explain why temperatures in the tract did not become a limiting factor in tolerance for extreme heat. It became evident that closer and more complete study of the total biothermal process was necessary for fuller understanding, and the present series was planned to incorporate humidities and air volumes, as well as temperatures. With such data both heat and mass balances can be calculated and the rationale of the temperature curve more thoroughly elucidated.

A number of papers on respiratory temperatures, humidities and heat exchanges have appeared in the literature. They vary in the temperature and humidity ranges considered, the methods used, and in the number of variables under measurement. Burch[3] presents the most complete series on "neutral" temperature exposures. Loewy and Gerhartz[7] and Pfliederer and Less[10] covered cold and "neutral" zones, while Seeley[11] explored a large range, 20 to 130°F. In many of the papers only portal-to-portal measurements were taken, but Seeley drew respired air samples also from two sites in the nasopharynx, and Christie and Loomis[5] utilized Haldane-Priestley samples and other alterations in the respiratory mechanics to infer temperature and humidity conditions in the deep passages and lungs. Although they involve heating stresses of a much higher order of magnitude, the experiments of Moritz, Henriques and McLean[8] on dogs establish damage and temperature levels at several points in the respiratory tract.

The purpose of this investigation is to determine the temperature, humidity and heat quantities of the inspired and expired airs in order to determine (1) respiratory heat exchange under high temperatures and a range of humidities, and (2) to obtain data from which extrapolations may serve to indicate the critical temperatures which exceed human tolerance.

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Inspired Air

The test chamber which Blockley and Taylor[2] used in heat tolerance experiments together with its temperature and humidity control served to furnish the controlled atmosphere for the inspired air of the subjects. This chamber is equipped with temperature and humidity controls: wet and dry bulb thermocouples and a dew point meter give a check on the temperatures and humidities actually attained.

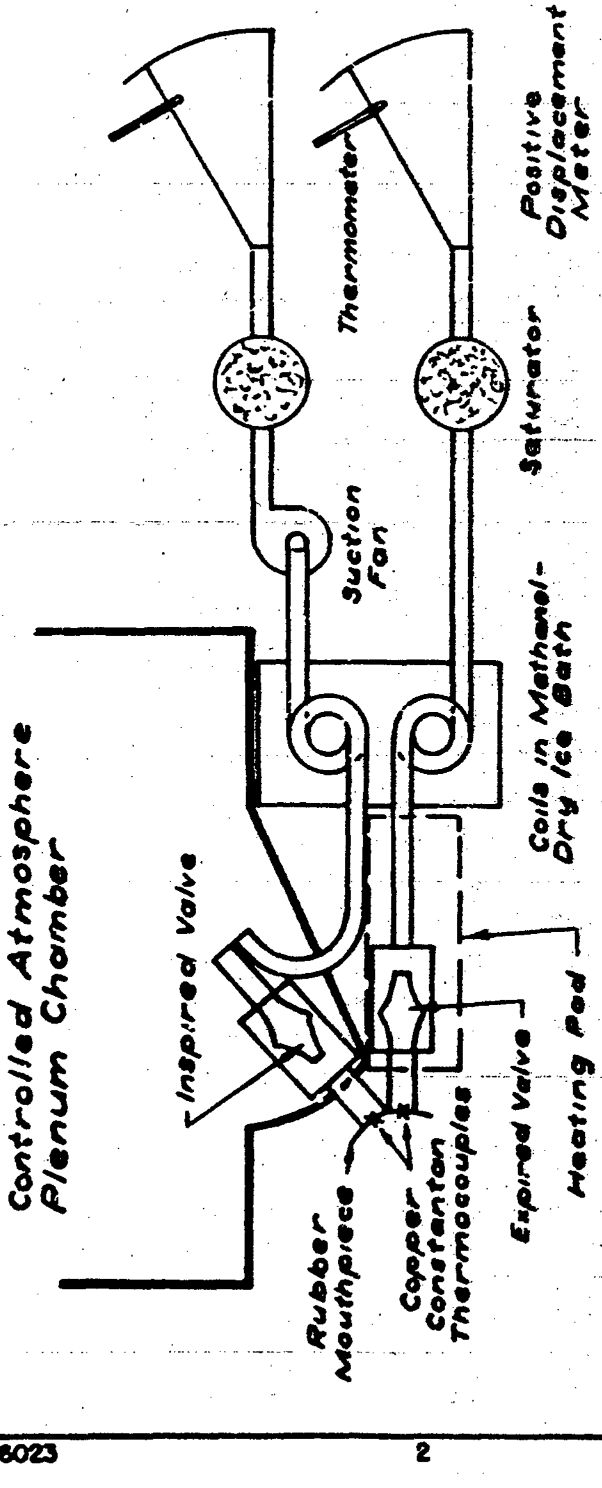
Respiratory Measurement System

This system consisted of: (1) mouthpiece; (2) thermocouples to measure air temperature at the mouthpiece (at portal of mouth); (3) "freeze-out" coils to collect vapor; and (4) respiratory gasometer. Similar circuits were furnished for expired and inspired air, the latter being sampled from the inspired airway. The equipment is schematized in Fig. 1.

The mouthpiece was made by cementing two Collins single channel mouthpieces together. These were chosen because they had a large opening, hence a low resistance. The tubing used to connect the valve set to the condensing coil was of flexible plastic so chosen to avoid the absorption of moisture.

The respiratory thermocouple equipment, designed to enable accurate measurement of the rapidly fluctuating temperatures of the air stream, consisted of a self balancing electronic potentiometer giving an ink record of thermocouple temperatures on a direct-writing oscillograph. The response of this unit is flat up to several cycles per second. It draws practically no current from the thermocouples, and is unaffected by line voltage fluctuations. The instrument was used in conjunction with fine butt-welded thermocouples constructed from number 40 gauge copper and constantan wire. These couples were found to follow air temperatures very closely, irrespective of the respiration rate.

The tabulated inhaled and exhaled air temperatures are the mean values of at least ten readings, five taken during the first half of the



Sketch of Equipment

Figure No. 1

test and five in the last half. As a check, a temperature record was kept for the entire duration of one experiment, and the average of all readings was found to be within 0.2°F of the average obtained by the method reported here. Fig. 1 is a typical temperature tracing and the resulting temperature recorded. These temperature measurements are probably the limiting factor in the accuracy of the derived quantities, such as heat exchange.

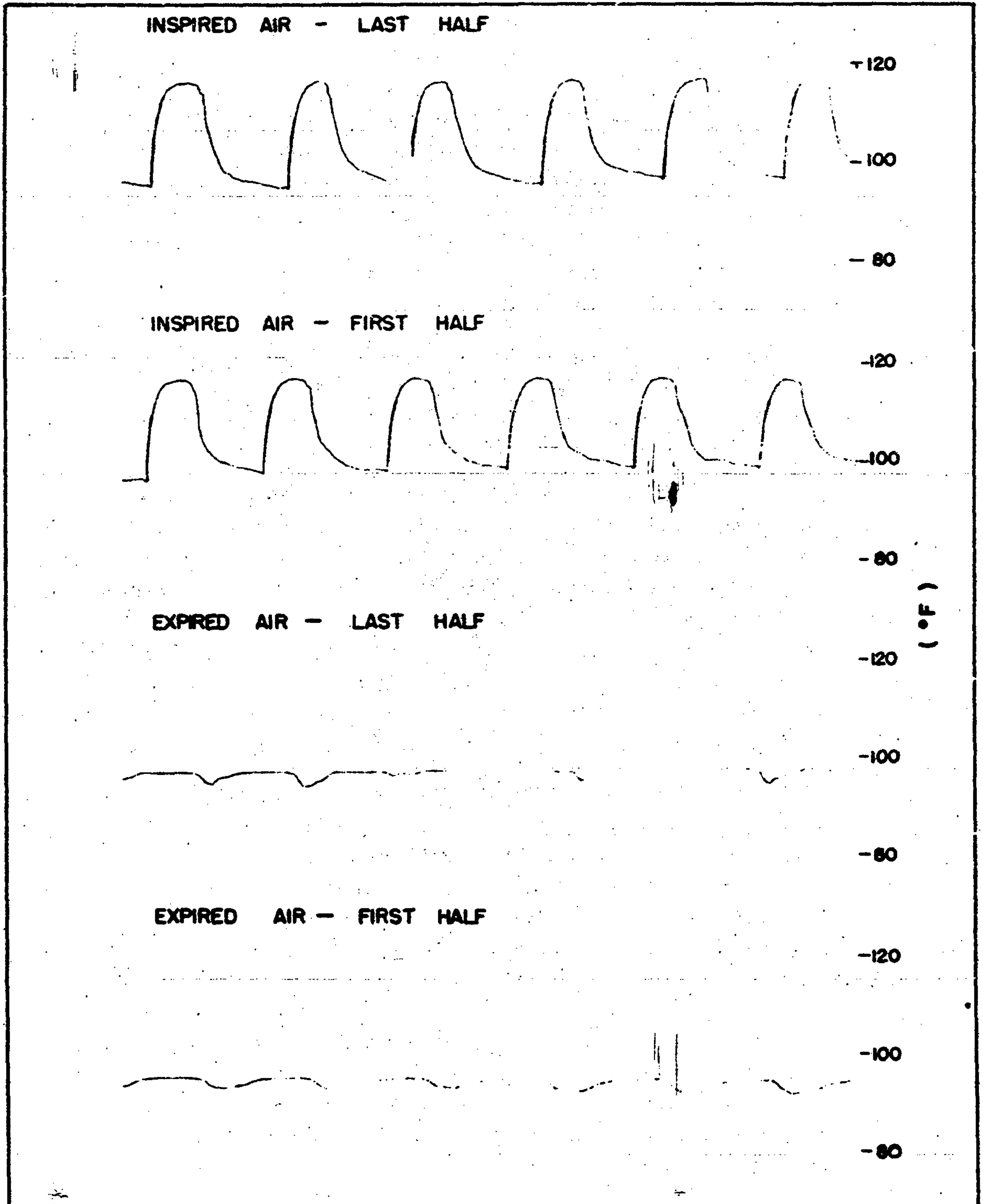
Table 1 gives an example from exp. M-4

TABLE I. SAMPLE TEMPERATURE DATA

Inspired		Expired	
First half	Last half	First half	Last half
116.8	116.0	94.5	97.0
116.7	116.2	94.7	97.0
116.8	116.0	94.8	97.0
116.8	116.4	94.8	97.0
117.0	116.8	94.8	97.0
116.8	117.0	94.8	97.2
Average 116.6°F		95.9°F	

The freeze-out coils were made of 0.75 in. diameter pyrex glass tubing and were formed into four-turn spirals 3.5 in. diameter, sufficiently light to permit weighing on a 200 gram analytical balance. For water vapor collection the coils were immersed in a methanol-dry ice bath, the temperature of which was approximately minus 100°F. In operation it was found that no liquid was formed; the water going directly from the vapor phase to the solid phase, forming snow. This snow was collected in the coils by a copper wire screen with varying hole size so that the snow was trapped gradually and plugging was prevented.

Respiratory volumes were determined by a positive displacement metabolism gasometer, and were corrected to standard temperature and pressure. A possible error existed in the fact that this volume was considered as saturated. Previous tests on the percent saturation of the collected air sample gave an average value of 92%, extremes being 90 and 95%. The error which this makes in the measured volume is well


INSPIRED AIR - LAST HALF

INSPIRED AIR - FIRST HALF

EXPIRED AIR - LAST HALF

EXPIRED AIR - FIRST HALF

FIGURE 2

below one percent and was neglected.

Calibrations

The temperature and volume measuring equipment had previously been calibrated so that it was only necessary in this series of experiments to run the following daily check. The thermocouple amplifier was set with reference to a precision potentiometer, and the thermocouples in the mouthpiece, when in a steady state, were checked against thermocouples connected directly into the potentiometer. A calibration factor was thus found and applied for the experiment.

Since the packing in the humidity coils was determined by trial and error the collection system had to be calibrated. The procedure was essentially that used by Burch.[3] Many preliminary tests were run but the final checks consisted of two calibration series.

Series A had as its object to show that the first of two coils placed in series collected all but a trace of water from the air passing through the system. All the air for these tests was taken from the same location in the plenum chamber as was eventually used to bring inspired air to the subjects. The dew point calculated from the water collected in the first coil was also checked against the dew point as given by the dew point meter (considered accurate to ±1°F). The air samples used to calibrate the coils were chosen to represent the possible extremes of conditions which would be encountered during actual tests. The results are shown in Table II.

The object of calibration series B was to show that a known amount of water could be recovered by a single coil. Three coils were used in this test: Coil A, a saturating coil containing packing thoroughly wet with distilled water; Coil B, a condensing coil in series with saturation coil A; Coil C, a condensing coil in parallel with A, B to determine the water content of the air entering coil A.

Thus:

$$\text{Weight gain C} + \text{Weight loss A} = \text{Weight gain B}$$

It was concluded that the resultant low errors (Tables II and III) justified the use of these coils for the determination of the water content of inspired and expired air.

TABLE II. HUMIDITY CALIBRATION A

Control setting	Dew Point (°F)		Coil No. 2	
°F - in. Hg	observed	calculated	weight gain	% wt. gain*
200 - 1.18	87	87.6	-0.0001	-0.01
200 - 1.18	84	83.7	+0.0003	+0.04
200 - 1.18	82	81.3	+0.0052	+1.19
120 - 1.18	81	79.5	+0.0020	+0.38
120 - 0.79	80	77.9	+0.0018	+0.27
Room Air	48	48.7	+0.0010	+0.41
115 - 1.85 over	98	102.2	+0.0002	+0.01
115 - 1.85 over	98	100.1	+0.0001	+0.01

$$\text{*Percent weight gain} = \frac{(\text{Weight gain coil No. 2})}{(\text{Weight gain coil No. 1})} \times 100$$

TABLE III. HUMIDITY CALIBRATION B

Weight gain C	Weight loss A	Total	Weight gain B	Percent error*
0.1024	0.5479	0.6503	0.6559	+0.85
0.0975	0.5681	0.6656	0.6700	+0.66
0.2687	0.8618	1.1305	1.1250	-0.42
0.2718	0.9378	1.2097	1.2086	-0.09

$$\text{*Percent error} = 100\,\frac{[B - (C + A)]}{C + A}$$

SECTION II - SUBJECTS AND EXPERIMENTAL PLAN

Subjects

The five subjects were male, white adults working in the Engineering Department of the University of California at Los Angeles. They were between the ages of 22 and 38. Their respiratory patterns differed considerably, although this was not considered in their choice.

TABLE IV. DATA ON SUBJECTS

Subjects	Age	Height (in.)	Weight (lbs)	Body Area (sq. ft.)	Symbol
E.R.H.	38	72.0	150	20.3	+
M.V.B.	28	72.0	146	20.0	○
J.[illegible]	32	70.5	153	20.1	△
L.D.	22	67.5	155	19.6	□
G.L.T.	28	70.5	130	18.8	●

Experimental Routine

The night preceding an experiment the coils were washed and dried in a hot air stream. In the morning after all routine checks had been made on the equipment, the coils were weighed. After the subject had rested for 20 minutes to insure a standard resting state the inspired air controls were checked and the test was run. Each test was continued until approximately 30 liters of air had been respired. The coils were then dried on the outside by wiping and left to stand in a rack in the room air. After about an hour and a half the coils were repeatedly weighed until a constant value was obtained.

Range of Conditions

TABLE V. RANGE OF INSPIRED AIR TEST CONDITIONS

Air Temperature (°F)	Air Temperature (°C)	Vapor Pressure (in. Hg)	Vapor Pressure (mm Hg)
Room Air	21 - 24	Range = 0.17 - 0.21	4.0 - 5.3
120	49	0.39, 0.79, 1.18	10, 20, 30
160	71	0.39, 0.79, 1.18	10, 20, 30
200	93	0.39, 0.79, 1.18	10, 20, 30

The room air samples served to establish a norm and checks against previously published data. The other conditions were chosen, within the limits of the testing equipment, to sample a range of temperature and humidity of inspired air. It should be noted that the low humidity (0.39 in. Hg) environments were not under wet bulb control; rather the air at ambient humidity was passed through a silica gel drier with no vapor added. Whatever water content of the air occurred under these circumstances was determined as the test was run.

Special Conditions of Experiments

It should be pointed out that the conditions of these experiments depart in some respects from usual conditions of total exposure.

(1) Subjects were in a standard resting state, not basal: they sat quietly for a period of at least 20 minutes before the test.

(2) Body temperature, though not measured, was assumed to remain unaltered since the ~~subject~~ was normally clothed and in a comfortable environment.

(3) The short time of exposure, approximately five minutes, minimized the tendency to heat up the respiratory tract.

(4) Portal-to-portal measurements were the subject of consideration, so that all experimental arrangements were designed to give accurate temperatures, humidities and air volumes at that point.

(5) Oral breathing was routine, with the nose closed off by a clamp.

SECTION III - HUMIDITY AND ENTHALPY CALCULATIONS

The following postulates are appropriate to the problem at hand:

(1) Respired air is a perfect gas.

(2) The water added by the respiratory tract to the respired air was at standard body temperature (98.6°F).

(3) The volumes of inspired and expired air are the same.

Regarding point (3) the following calculation was made. Best and Taylor[1] give an average respiratory quotient of 0.85 for adults on a normal diet, and an inspired-expired change in the CO_2 content of approximately four percent of the total volume. Respiratory quotient is defined as the ratio of the volume of CO_2 eliminated to the volume of O_2 absorbed. Consequently, the net volume change from inspired to expired air would be $(1 - 0.85)(4/100) = 0.6\%$. After considering the magnitude of this error it was decided the difference could be neglected.

The BE system of units was used, except in certain key charts and tables, and when comparing our results with previous publications. Most of the terms of the total body heat exchange have been found to have a high correlation with body surface area, so it has been the practice to refer the heat exchange of the respiratory tract to unit body surface area per unit time. However, most of the respiratory heat and water exchange, it will be shown, have more regular relations with the unit mass of air respired than with the mass or volume rates, or surface area. Consequently, moisture content and enthalpies have been referred to one pound of dry air. This is also the custom in engineering calculations of heat and mass transfer in air-vapor systems, to which the present problem is analogous in many of its aspects.

Table VI presents the calculation equations and notation. The sign convention for q_v and ΔH is such that (+) means a heat gain to the body and (-) is a heat loss.

TABLE VI. CALCULATION EQUATIONS AND NOTATION

Mass of respired air: $M_a = [(P - \phi p_s)\ V\ 144] / R\ T$ (1)

Humidity: $W = M_w / M_a$ (2)

Specific enthalpy, inspired air:

$$h_i = .24\ (t_i - t_b) + .444\ W_i\ (t_i - t_b) + L_{98.6}\ W_i \qquad (3)$$

Specific enthalpy, expired air:

$$h_e = .24\ (t_e - t_b) + .444\ W_e\ (t_e - t_b) + L_{98.6}\ W_e \qquad (4)$$

Specific enthalpy difference: $\Delta H = h_i - h_e$ (5)

Percent rel. humidity: $\phi = 100\ p / p_s$ (6)

Percent saturation: $\mu = 100\ W / W_s$ (7)

P, p, p_s = barometric pressure; partial pressure; partial pressure, saturated, of water vapor (lb / in^2)

M_a, M_w = mass of dry air, mass of water vapor (lb)

W, W_s, ΔW = humidity, humidity at saturation, humidity difference, (lb vapor / lb dry air)

V = volume of respired air (ft^3)

T, t_i, t_e, t_b = absolute, inspired, expired, body temperatures (°F)

$L_{98.6}$ = latent heat of vaporization at 98.6°F (Btu / lb)

h_i, h_e = inspired, expired enthalpies (Btu / lb)

R = gas constant for air = 53.35

q_v = respiratory heat exchange (Btu / hr ft^2)

θ = time (hr)

A_b = body surface area (ft^2)

SECTION IV - RESULTS

All basic data and the principal quantities derived by calculation are given in the Appendix. The various interrelationships, from which major conclusions are drawn, are presented graphically or in the form of mathematical equations. The analysis has been directed toward the following points: (1) respiratory enthalpy difference as a function of inspired air properties; (2) expired air properties as a function of inspired air properties; (3) comparison of respiratory with total body tolerance contours; and (4) the effects of respiratory rate and volume upon the heat and mass quantities.

Specific Enthalpy Difference

Preliminary plots of the data indicated that ΔH was the heat exchange parameter which would offer highest correlations with inspired quantities. It was also clear that both temperature and humidity affected ΔH and accordingly multiple regression solutions were carried through for each subject, by the method outlined by Peters and Van Voorhis.[9] The multiple regression, obtained by the method of least squares, is of the form

$$X = a + b_{yx.z} Y + b_{zx.y} Z$$

where,

X = dependent variable

a = intercept value

Y, Z = independent variables

$b_{yx.z}, b_{zx.y}$ = partial regression coefficients

The correlations proved so high and closely similar that values for the total data were also computed. Table VII gives the statistical values and regression equations, while the fit of the total equation is indicated by Fig. 4.

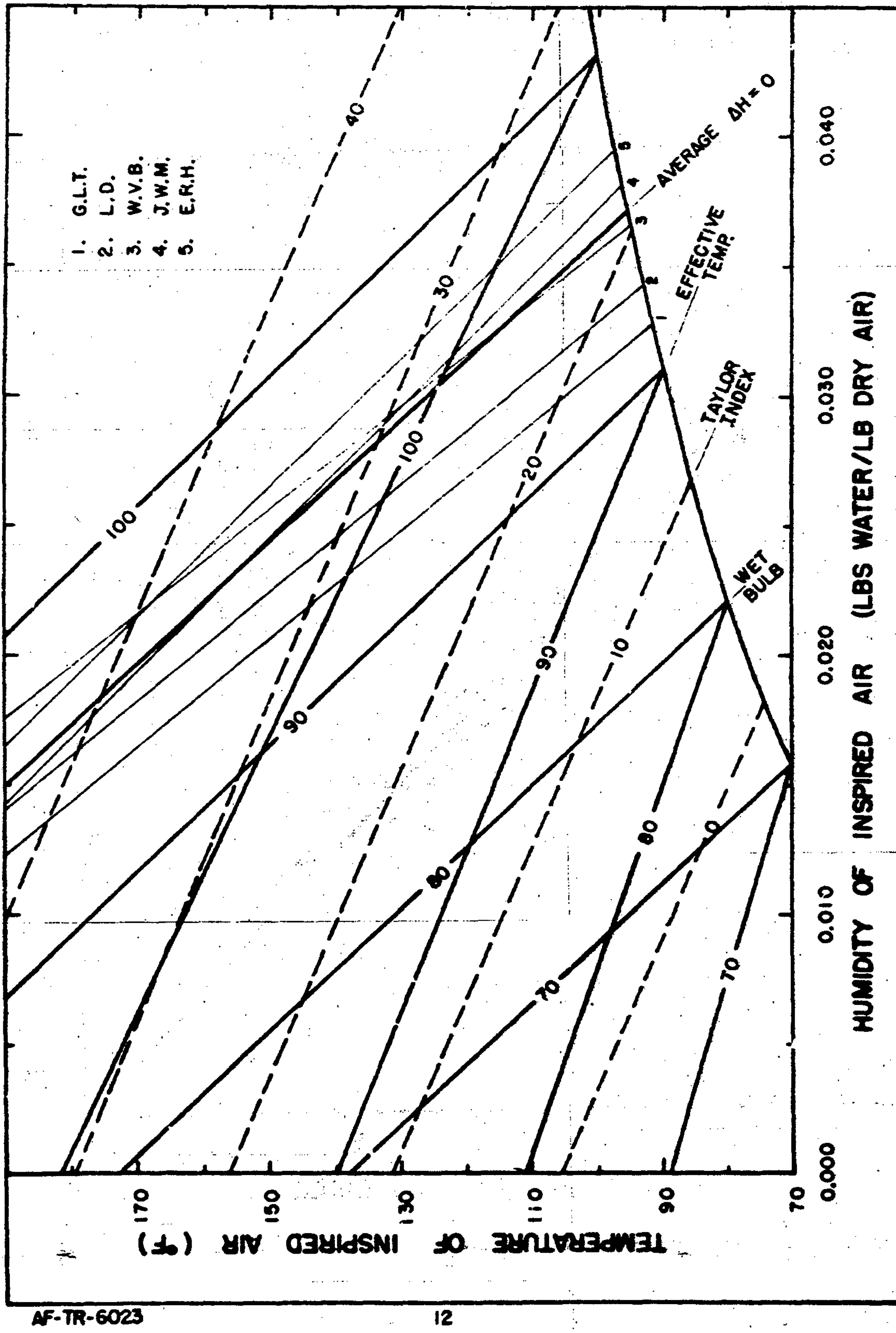

1. G.L.T.
2. L.D.
3. W.V.B.
4. J.W.M.
5. E.R.H.
AVERAGE ΔH = 0
EFFECTIVE TEMP.
TAYLOR INDEX
WET BULB
1
2
3
4
5
100
90
80
70
40
30
20
10
0
100
90
80
70
90
80
70
TEMPERATURE OF INSPIRED AIR (°F)
170
150
130
110
90
70
HUMIDITY OF INSPIRED AIR (LBS WATER/LB DRY AIR)
0.000
0.010
0.020
0.030
0.040

FIGURE 3

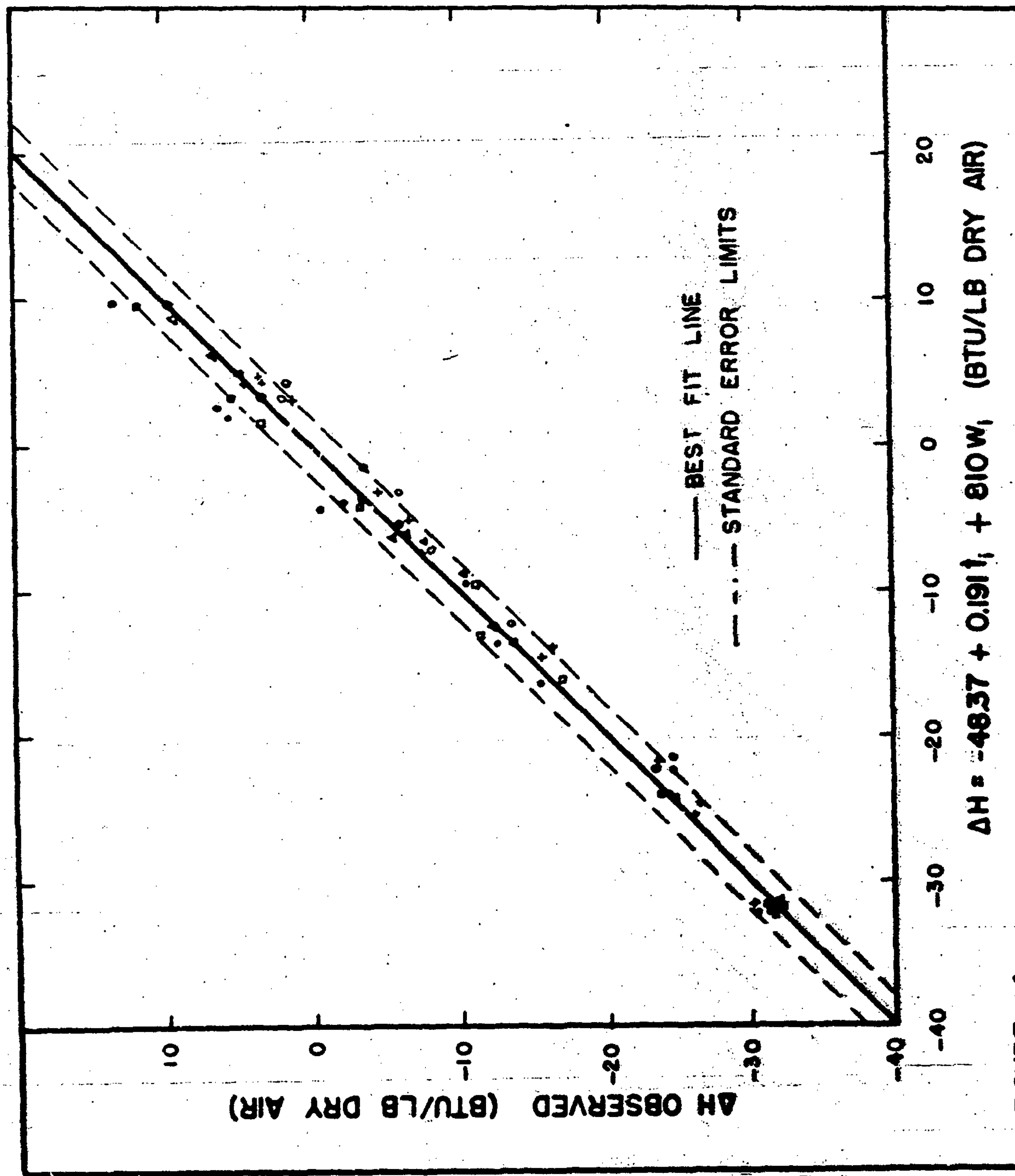

ΔH OBSERVED (BTU/LB DRY AIR)
10
0
-10
-20
-30
-40
-40
-30
-20
-10
0
10
20
BEST FIT LINE
STANDARD ERROR LIMITS
ΔH = -48.37 + 0.191 t_i + 810 W_i (BTU/LB DRY AIR)

FIGURE 4

TABLE VII. STATISTICAL SUMMARY: ΔH REGRESSION

Variables:

x = ΔH, specific enthalpy difference (Btu / lb)

y = temperature of inspired air (°F)

z = humidity of inspired air (lb / lb)

Correlations:

	F.R.L.	W.V.B.	J.T.L.	L.D.	G.L.T.	Total
zero order						
r_{xy}	.899	.907	.830	.798	.807	.851
r_{xz}	.849	.914	.792	.831	.814	.820
r_{yz}	.541	.608	.383	.331	.322	.431
multiple						
$R_{x(yz)}$	.997	.996	.975	.999	.997	.989

Regression equations:

F.R.L.	$\Delta H = -48.34 + 0.189\ t_i + 758\ W_i$
W.V.B.	$\Delta H = -48.57 + 0.175\ t_i + 873\ W_i$
J.T.L.	$\Delta H = -46.69 + 0.190\ t_i + 742\ W_i$
L.D.	$\Delta H = -46.95 + 0.182\ t_i + 877\ W_i$
G.L.T.	$\Delta H = -48.37 + 0.194\ t_i + 935\ W_i$

The total regression equation is:

$$\Delta H = 0.191\ t_i + 810\ W_i - 48.37\ ; \quad SE_{est} = \pm 2.01$$

Since interindividual variations proved so small in relation to the degree of interrelationship of other variables, and since the number of cases, five, was too small for a thoroughgoing analysis of individual differences, it was decided at this point to pool the data in all subsequent treatments. Graphic presentations of all important fits, with the individual subjects denoted by symbol will enable the reader to judge the validity of this procedure. In the case of the regression for ΔH, Fig. 4 shows that individual plots fall closely about the line of relationship. Those for C.L.T. tend to be high, those for [illegible] tend to be low, but the other three subjects do not show significant differences.

Fig. 3 displays the regression lines on a temperature humidity plot. The most important finding here is that the total regression lines agree in slope closely with wet bulb lines. This is a significant empirical finding, but more important it discloses a heat and mass transfer process fully analogous to a wet bulb. Accordingly, a least squares fit was made between wet bulb of the inspired air and ΔH. The plotted points and line of relationship are given in Fig. 5. The predictive equation is:

$$\Delta H = 0.01047\, t_w^2 - 0.8\text{[illegible]}\, t_w - 15.81 \qquad \sigma_{est} = \pm 1.59$$

Upon this chart are also drawn Effective Temperature lines and lines of equal physiological effect** in order to permit comparison of ΔH with these indices of thermal equivalence for the body as a whole.

Properties of the Expired Air as Functions of Inspired Air Conditions

In order to give a more complete picture of the respiratory process, the temperature, humidity, percent saturation and enthalpy of expired air have been plotted on the same chart, Fig. 6. For this purpose regression equations were computed, as given in Table VIII. Percent saturation was derived from the temperature and humidity values and the contours are eye fits drawn with a french curve.

Largely as a matter of convenience, the relations between these variables, except percent saturation, and inspired wet bulb have been computed, assuming the equations are second degree parabolas. The equations are given in Table IX. The curves are found in Fig. 7.

Respiratory Volume and Rate as Functions of Inspired Wet Bulb

Since the temperature, mass and heat properties of the respiratory exchange correlate closely with inspired wet bulb, an adequate test of the possible effect of volume and rate should be their correlations with wet bulb. Accordingly, plots were made as shown in Fig. 8 and Fig. 9. It is apparent from these plots that no significant relations exist. Rather, each subject tends to maintain a characteristic level of rate and volume independent of inspired wet bulb. Subject L.D. showed highest rates and volumes throughout. In his first experiment the volume was 0.677 ft^3/min (19.2 liters/min) and the rate, 23. These excessive values declined to about nine liters and rate of 16 for the duration of the series, as he became accustomed to the respiratory equipment. The individual average rates and volumes are shown in Table X.

TABLE VIII. STATISTICAL SUMMARY: EXPIRED AIR REGRESSIONS

Variables: Y = temperature of inspired air (°F)

Z = humidity of inspired air (lb / lb)

Dependent variable X	zero order r_{xy}	 r_{xz}	 r_{yz}	multiple $R_{x(yz)}$
$X = t_e$ (°F)	0.942	0.539	0.431	0.953
$X = \Delta W$ (lb / lb)	−0.222	−0.955	0.431	0.975
$X = H_e$ (Btu / lb)	0.758	0.758	0.431	0.915

Regression equations:

$$t_e = 86.9 + 0.066\ t_i + 57.4\ W_i \qquad SE_{est} = \pm 1.0$$

$$\Delta W = 0.02645 + 0.0000361\ t_i - 0.798\ W_i \qquad SE_{est} = \pm 0.00156$$

$$H_e = 24.51 + 0.0537\ t_i + 227\ W_i \qquad SE_{est} = \pm 1.66$$

TABLE IX. WET BULB EQUATIONS FOR EXPIRED AIR

$$t_e = 83.6 + 0.159\ t_w + 0.00008\ t_w^2$$

$$W_e = 0.02186 + 0.000126\ t_w + 0.0000003\ t_w^2$$

$$H_e = 25.58 - 0.01373\ t_w + 0.001514\ t_w^2$$

TABLE X. RESPIRATORY VOLUMES, RATES AND MASSES

Subjects	Resp. Volume (STP) (ft^3/min)	Resp. Volume (STP) (lit/min)	Mass dry air (lb/hr)	Resp. rate
E.R.H.	0.184	5.21	0.891	5.9
W.V.B.	0.204	5.78	0.988	7.1
J.N.M.	0.169	4.79	0.819	11.2
L.D.	0.369	10.45	1.790	19.5
G.L.T.	0.238	6.74	1.153	13.6
Average	0.233	6.59	1.128	11.5

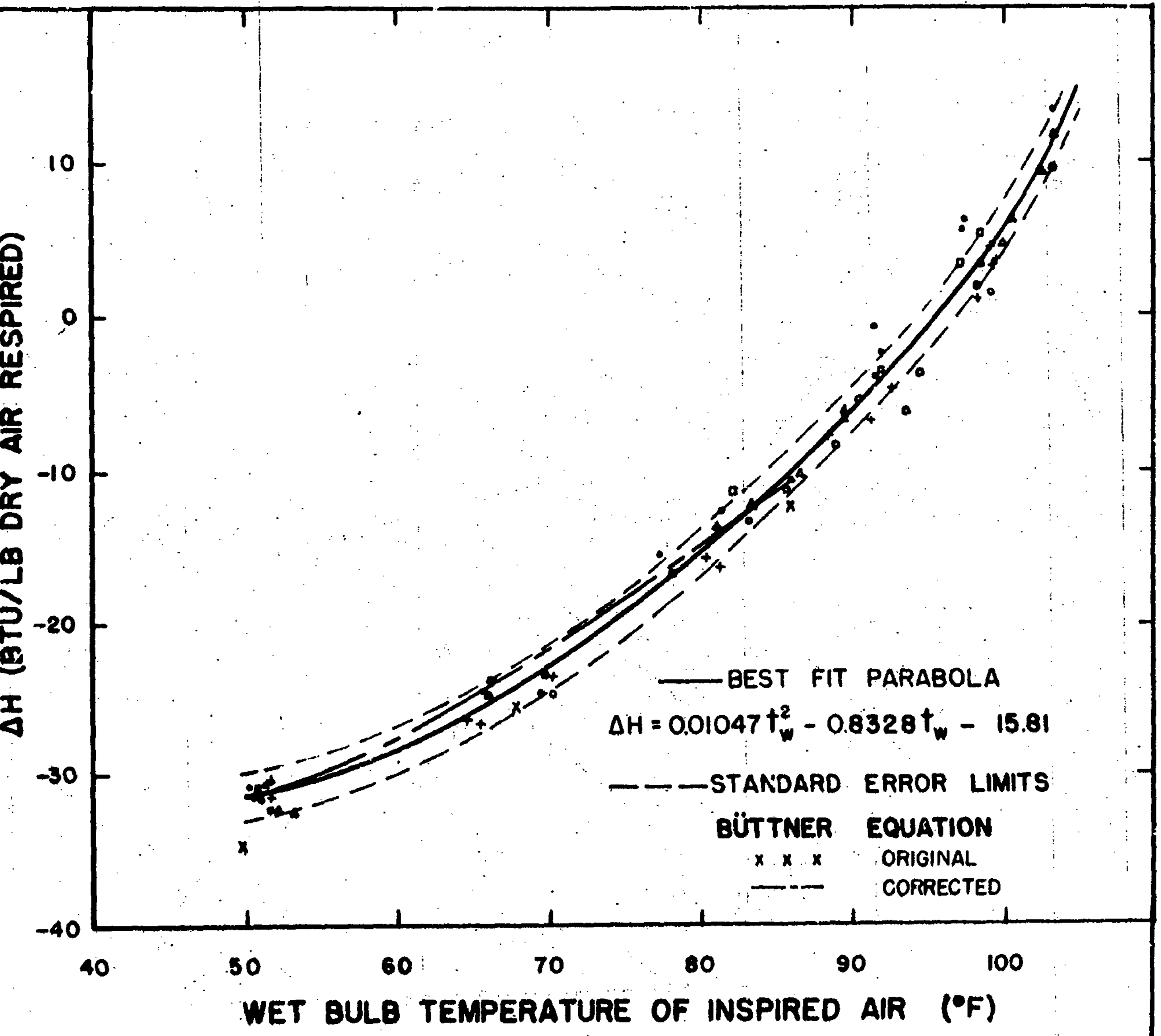

ΔH (BTU/LB DRY AIR RESPIRED)
10
0
-10
-20
-30
-40
40
50
60
70
80
90
100
WET BULB TEMPERATURE OF INSPIRED AIR (°F)
BEST FIT PARABOLA
$\Delta H = 0.01047 t_w^2 - 0.8328 t_w - 15.81$
STANDARD ERROR LIMITS
BÜTTNER EQUATION
x x x ORIGINAL
CORRECTED

FIGURE 5

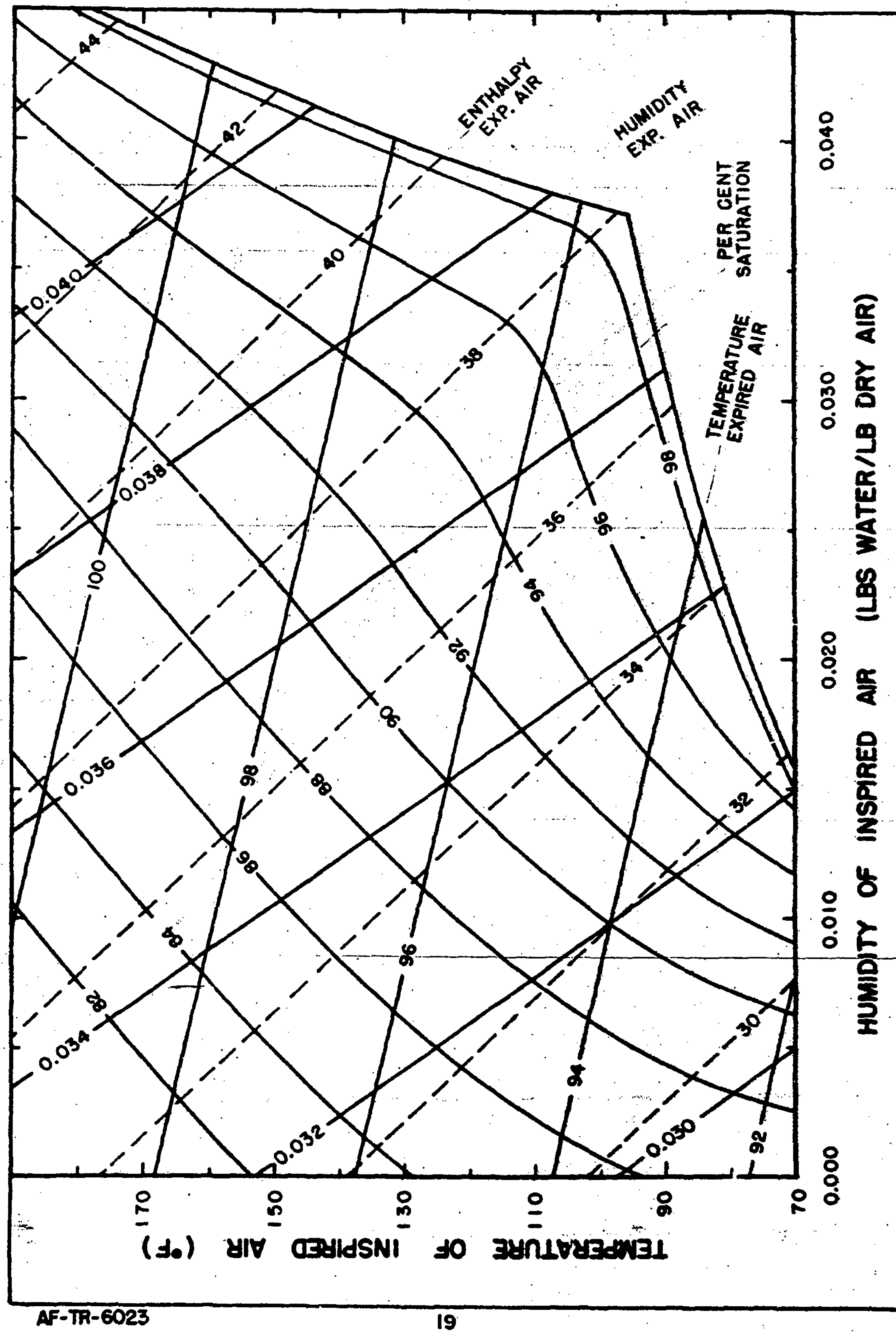

ENTHALPY EXP. AIR
HUMIDITY EXP. AIR
PER CENT SATURATION
TEMPERATURE EXPIRED AIR
44
42
40
38
36
34
32
30
0.040
0.038
0.036
0.034
0.032
0.030
100
98
96
94
92
90
88
86
84
82
HUMIDITY OF INSPIRED AIR (LBS WATER/LB DRY AIR)
0.000
0.010
0.020
0.030
0.040
TEMPERATURE OF INSPIRED AIR (°F)
70
90
110
130
150
170

FIGURE 6

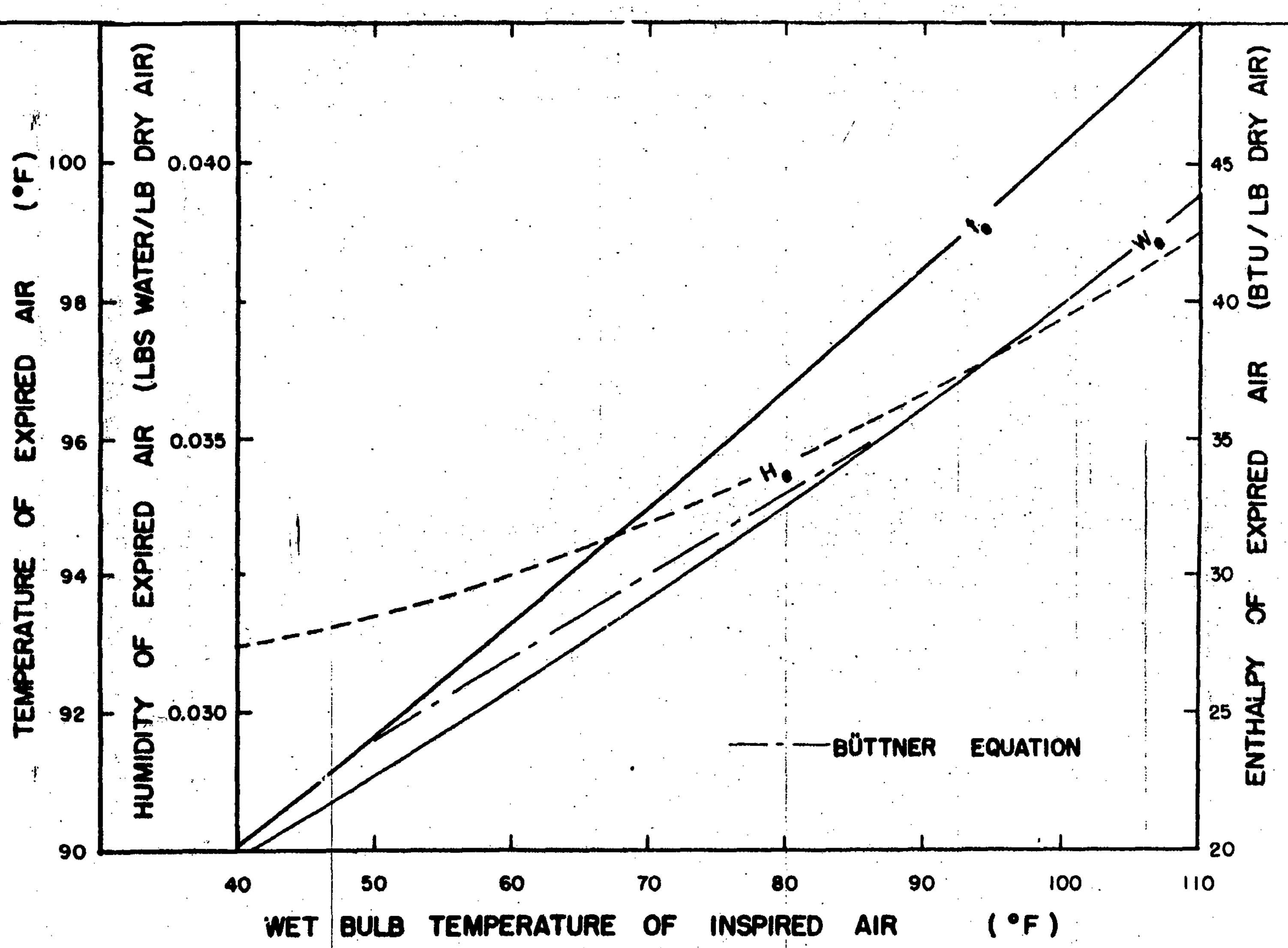

TEMPERATURE OF EXPIRED AIR (°F)
90
92
94
96
98
100
HUMIDITY OF EXPIRED AIR (LBS WATER/LB DRY AIR)
0.030
0.035
0.040
ENTHALPY OF EXPIRED AIR (BTU / LB DRY AIR)
20
25
30
35
40
45
WET BULB TEMPERATURE OF INSPIRED AIR (°F)
40
50
60
70
80
90
100
110
t_e
W_e
H_e
BÜTTNER EQUATION

FIGURE 7

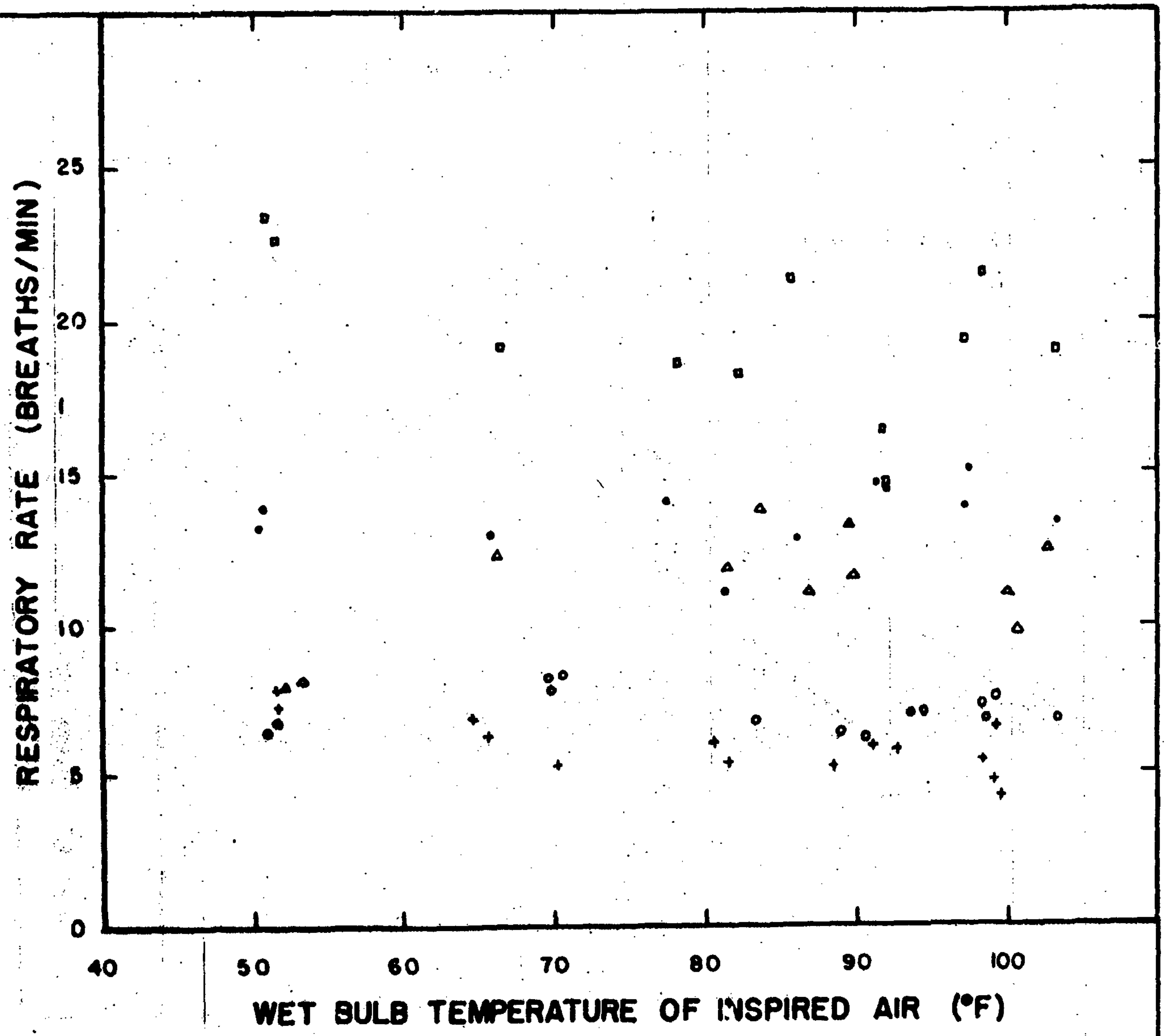

RESPIRATORY RATE (BREATHS/MIN)
0
5
10
15
20
25
40
50
60
70
80
90
100
WET BULB TEMPERATURE OF INSPIRED AIR (°F)

FIGURE 8

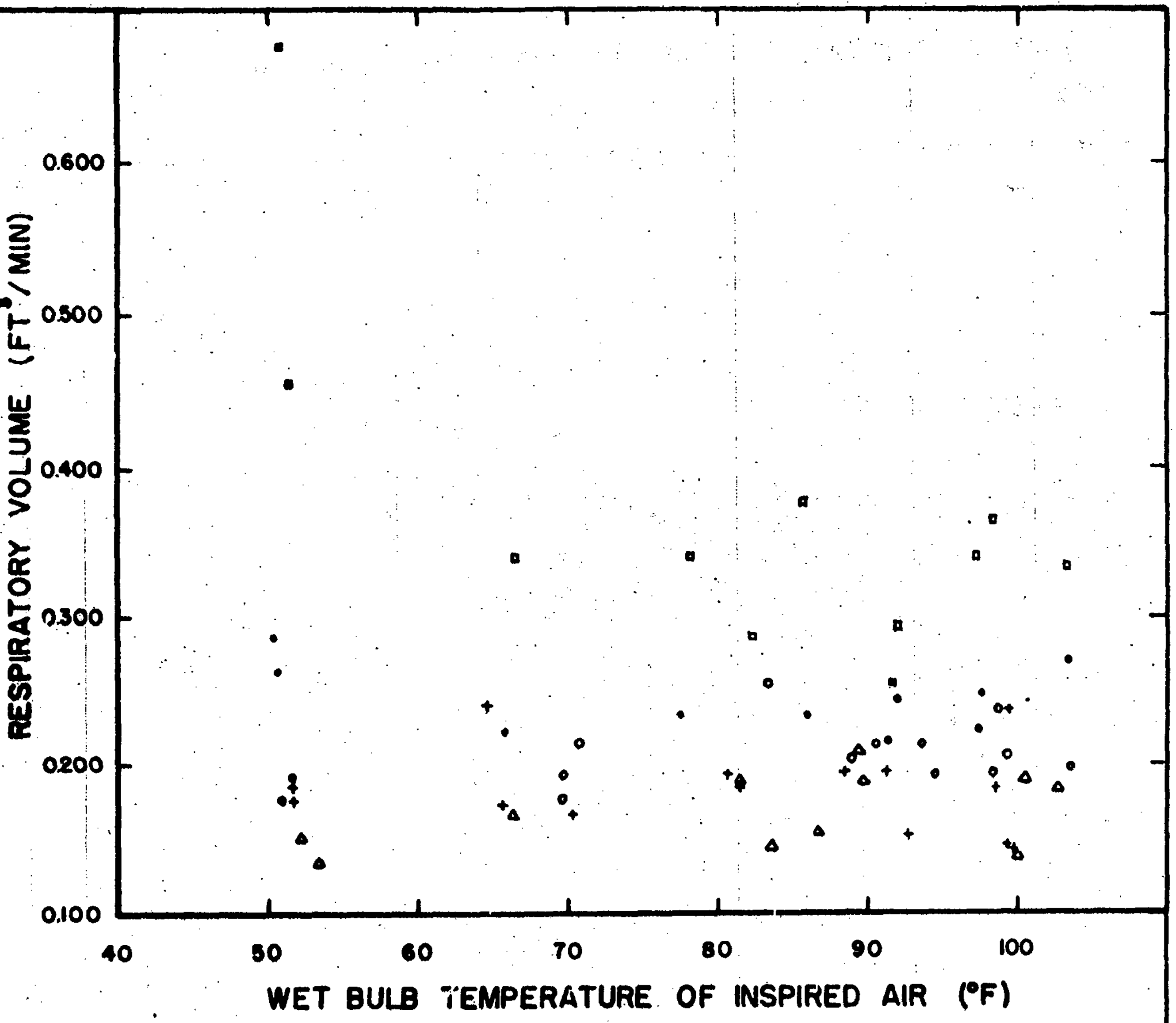

RESPIRATORY VOLUME (FT³/MIN)
0.600
0.500
0.400
0.300
0.200
0.100
40
50
60
70
80
90
100
WET BULB TEMPERATURE OF INSPIRED AIR (°F)

FIGURE 9

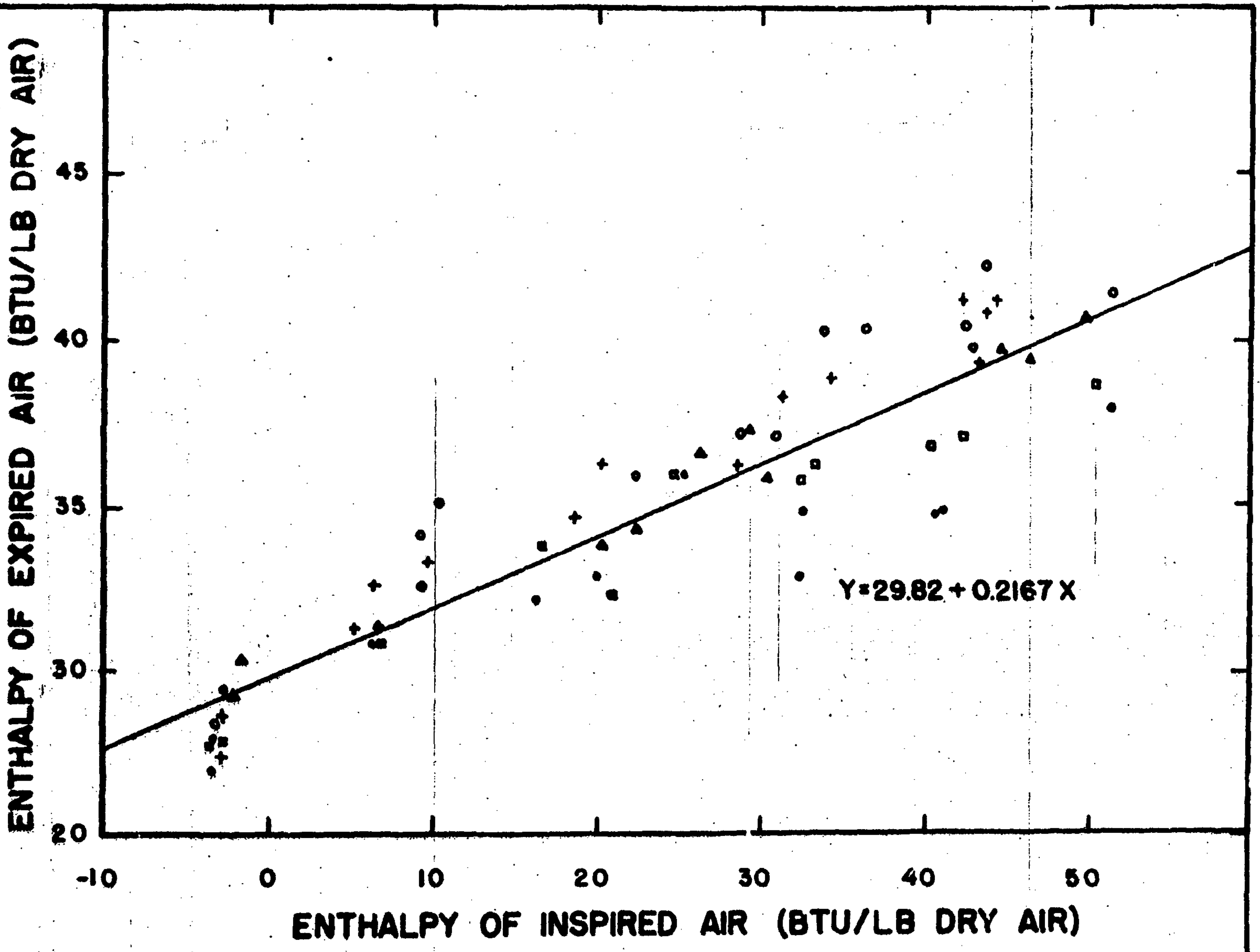

ENTHALPY OF EXPIRED AIR (BTU/LB DRY AIR)
45
40
35
30
20
-10
0
10
20
30
40
50
ENTHALPY OF INSPIRED AIR (BTU/LB DRY AIR)
Y=29.82+0.2167 X

FIGURE 10

SECTION V - DISCUSSION

Effect of Temperature and Humidity upon the Expired Air

It is clear from Fig. 6 that both temperature and humidity of the expired air are affected by the temperature and humidity of inspired air. All investigators[11,7,10,3] agree on the temperature relation; except Corlette[6] who assumes a constant temperature of 33°C for expired air. The humidity of expired air, on the other hand, is stated by several authors[10,6,4] to be saturated regardless of other conditions. The best evidence, however, is otherwise[5,3,11], and our data clearly show that unsaturation is the rule. Percent saturation of expired air is a direct function of inspired air humidity and an inverse function of inspired air temperature. Humidity of the expired air is seen from Fig. 6 to be closely related to humidity of inspired air but is only moderately affected by inspired air temperature. The partial dependence of temperature and humidity of the expired air upon the corresponding quantities in the inspired air is further corroborated by the correlations with wet bulb temperature, Fig. 7.

The basis for the influence of inspired air composition upon the expired air is largely to be found in reciprocal exchanges of heat and water between the respiratory tract and the respired air stream during the inspiration and expiration phases. These effects are best illustrated in the diagrams of Seeley[11] which show that even in the short traverse from nasopharynx to portal the expired air temperature rises if the preceding inhaled air was hot. Conversely the temperature falls if the inhaled air was cold. The simplest and probably entirely adequate explanation for these effects is that heat given to or extracted from the respiratory tract during inhalation is correspondingly extracted from or given to the exhaled air.

In regard to humidity changes, the surprising fact is that condensation apparently does not play an important role. Relative humidities (or percent saturations) of expired air in the present experiments were, except for two experiments, always less than 100% and typically were in the range 80 - 90%. Seeley[11] generally obtained like results. He found that, at a room temperature of 70°F, the inspired humidities always rose to over 90% in the position mid-way between portal and nasopharynx on inhalation, but at the same point on exhalation were reduced in relative humidity to about 80%. This is approximately accounted for by the higher temperature obtaining at this position during exhalation if no absolute humidity change occurred. Seeley further found that if the inspired air was cold, it was also relatively cool on expiration, but the expired relative humidity was in the range 80 - 90%, regardless of the relative humidity of inspired air.

Lung Temperature and Humidity

Lack of saturation of the expired air in the outer passages and at the portal raises the question of the state of lung temperature and saturation. No lung temperature data for humans are known to the authors but Walther, Bishop and Warren[13] report a lung temperature of 36.7°C in the calf and Loewy and Gerhartz[7] found 36.0°C for rabbits and 36.2°C for dogs. Saturation at such temperatures would give a vapor pressure of about 45 mm Hg as was found by Christie and Loomis.[5] The evidence therefore is that lung air must be nearly saturated, probably 95% or higher. Since the lung temperatures are, under usual conditions of inhaled air, the highest in the respiratory tract; the explanation for the partial unsaturation of the expired air must be sought in other processes such as adsorption on the mucous surfaces of the tract. In spite of the above estimates of lung temperature and those of various sites in the respiratory tract, the temperature at which water is added has been taken at the standard figure of 98.6°F (37.0°C) for the thermodynamic calculations.

Specific Enthalpy and Specific Enthalpy Difference

A good correlation is found between the enthalpies of inspired and expired air, as shown in Fig. 10. Even higher correlation is found when inspired enthalpy is plotted against specific enthalpy difference. This is largely the result of the greater range of the latter, since the residual variations about the lines of relationship are of similar magnitude. These correlations, those with humidity and temperature, Fig. 4, and those with wet bulb, Fig. 5, permit the straightforward interpretation that the respiratory tract exchanges sensible and latent heat in the same manner as a radiation shielded wet bulb thermometer. The evidence for this statement is as follows:

(1) From Fig. 3 it is noted that the empirical regression lines at

$\Delta H = 0$ scatter closely about the wet bulb line. Since ideal, or thermodynamic, wet bulb is an adiabatic process, these comparisons can be made only at $\Delta H = 0$.

(2) From Fig. 5 at $\Delta H = 0$ the inspired wet bulb is 95.5°F. With this value we can enter Fig. 7 and read the predicted humidity and temperature of the expired air, 0.0366 lb / lb and 99.4°F resp. By reference to a psychrometric chart this gives a wet bulb of 96°F. This checks closely with the wet bulb of the inspired air of 95.5°F. Therefore, sensible and latent heat exchanges take place at relatively constant wet bulb and total heat.

(3) There are minor divergencies from ideal wet bulb behavior. Water is added in the tract at a temperature higher than wet bulb. The expired air does not proceed to saturation; in the above instance it is 87%. However, the extent of these discrepancies is small in comparison to the extent of agreement.

Respiratory Heat Exchange

It is evident from the plots in Fig. 8 and Fig. 9 that no significant relationship exists in the data as a whole or for any individual subject. Over the range of the inspired wet bulbs concerned, each subject tended to maintain his characteristic rate and volume of breathing. Other workers have found different results. Pfliederer and Less[10] report that heat exchange varies as the 3.5 root of respiratory volume; Burch[3] found a high correlation between volume and heat exchange when different subjects are considered; but Loewy and Gerhartz[7] obtained inconsistent results with regard to this variable. Such studies, however, involved total immersion of the subject or animal in the environment of inspired air and humidity; while in the present study the respiratory tract only was exposed to these conditions. Consequently, the overall body thermal state was relatively unaffected and significant thermal stimulus to respiration was lacking.

The respiratory heat exchange may be calculated from the equations:

$$q_v = (M / A_b\ \theta)\ [-48.37 + 0.191\ t_i + 810\ W_i]$$

or

$$= (M / A_b\ \theta)\ [-15.81 + 0.0105\ t_w^2 - 0.833\ t_w]$$

The grand average of $M = 0.0570$ lb / hr ft^2 for the present series may be used, or for a specific case where respiratory volume or mass is known, q_v can be calculated with use of the bracketed terms.

Comparison to Previous Work

Room temperature experiments in the present series may be compared with those of Burch[3], both environments averaging around 70°F. Table XI presents the comparison, expressed in the units employed by Burch.

TABLE XI. COMPARISON OF ROOM TEMPERATURE DATA WITH THOSE OF BURCH

	Burch	UCLA
Room air temperature (°C)	20 - 21	21 - 24
Room relative humidity (%)	55 - 60	20 - 40
Expired air temperature (°C)	33.19	33.2
Expired relative humidity (%)	88.2	88.2
Respiratory volume (liters / m^2 10 min)	38.29	41.1
Water loss (gm / m^2 10 min)	0.88	1.21
Heat exchange (kg-cal / m^2 10 min)	0.627	0.828

The agreement is remarkable as regards expired air temperature and humidity, but only fair for water loss and heat exchange. In part, the latter can be explained by the lower room humidity in the present experiments, which, it has been shown, increases the water loss and therefore the latent heat. In the above comparison, the heat associated with the excretion of CO_2, as computed by Burch, has been omitted, in order to restrict consideration to the sensible and latent heat exchanges which are the subject of present study.

More general formulations have been presented by Büttner[4], as taken from the data of Pfliederer and Less[10]. He gives for expired air,

$$t_e = 32 + 0.0378\,\bar{A}_i, \quad (^\circ C)$$

and for respiratory heat exchange,

$$q_v = 0.312\,V\,(\bar{A}_e - \bar{A}_i), \quad (\text{cal / min})$$

where, the new terms are,

$\ddot{A}_i$, $\ddot{A}_e$ = equivalent temperatures* of inspired and expired airs, derived from the equation:

$$\ddot{A} = t_w + 2\,p_{s\,(at\ t_w)}$$

and all temperatures are in degrees C. By appropriate conversions the curves of these equations can be compared with those of the present data. On Fig. 7 the plotted expired air curve of Büttner agrees approximately at a wet bulb of 50°F but diverges so that at 86° a 2° difference exists between the curves. We have no explanation for this discrepancy, and no further check is possible, since neither Büttner nor Pfliederer and Less present the basic data.

Converting the second Büttner equation to ΔH as a function of wet bulb, by utilizing the average respired air mass and surface area characteristics of the present experiments and subjects, a curve was obtained which could be plotted on Fig. 5. One notes that it everywhere falls below the curve of our data. Büttner, however, following Pfliederer and Less, asserts that the expired air is always saturated. Recalculation of $\ddot{A}_e$ from the value based on saturation to that actually found in our experiments gives a corrected Büttner curve which much more closely agrees with that for the present data. The Büttner equation may therefore be said to yield similar results, when corrected for the erroneous assumption of saturated expired air.

Subjective Reports

It has been noted that in another series of heat exposures up to 240°F there were found to be no critical sensations of heat or burning referred to the respiratory tract. The same may generally be said for the present experiments. Those experiments which were calculated to give a heat gain to the respiratory tract; namely 200°F and 1.18 in. Hg, caused three of the five subjects to report that the inspired air "set the teeth on edge". The comments on the other 160°F experiments were that the air was "warm" or "dry", and 120°F air was not sensed as different from room air.

---

* The equivalent temperature, $\ddot{A}$, is that commonly defined in meteorological literature as the "adiabatic equivalent temperature" which the air would have if totally dry and at the same pressure.

Comparative Thermal Equivalence Lines

The lines of ΔH on Fig. 3 may be considered thermal equivalence contours for the respiratory tract, and from the close parallelism to wet bulb lines the latter may also be said to define thermal equivalence contours. The surprising capacity to cool high temperature air through humidification can best be expressed by a comparison. At 185°F and .010 lb / lb the ΔH is zero, and therefore no net heat load is imposed upon the respiratory tract. Under the same conditions the overall body net heat exchange is strongly unbalanced in favor of a gain. Thus, the gain from radiation, convection and metabolism would approximate 3700 Btu / hr, the loss due to evaporation from the skin would not be greater than 3000 Btu / hr. Consequently heat accumulation occurs at the rate of 700 Btu / hr and the body temperature rise would be of the order of 5 - 6°F per hour. Actually, the average subject tolerates such an exposure only 40 minutes.[2] Thermal equivalence lines for the total body based upon a physiological index[12] and on the effective temperature scale are plotted comparatively with ΔH on Fig. 3. The slopes illustrate what is now well known, that total body heat balance does not obey the heat and mass transfer laws of the wet bulb, but as clearly shown here, the respiratory heat balance does so very closely.

SECTION VI - SUMMARY AND CONCLUSIONS

1. Specific enthalpy difference between inspired and expired airs proved to be the most fundamental heat quantity:

    (a) as judged by satisfactory predictive relationships which are independent of rate and volume of respiration;

    (b) as established by satisfactory theoretical accountings for the heat and mass transfer process.

2. By setting specific enthalpy difference equal to zero it was found that inspired and expired wet bulb temperatures agreed very closely. This permits the interpretation that adiabatic sensible and latent heat exchanges between inspired and expired air take place at constant total heat.

3. Predictive equations have been developed as follows:

$$\Delta H = 0.191\, t_i + 810\, W_i - 48.37\,; \qquad SE_{est} = \pm 2.01$$

$$\Delta H = 0.0105\, t_w^2 - 0.833\, t_w - 15.81\,; \qquad SE_{est} = \pm 1.59$$

4. The temperature, humidity and enthalpy properties of expired air are described mathematically and graphically.

5. Discussion of these results with other investigations in the literature, where comparison is justified, reveals satisfactory agreement when states of unsaturation of the expired air are considered.

REFERENCES

1. Best, C.H. and N.B. Taylor
The Living Body
H. Holt and Company, New York

2. Blockley, W.V. and C.L. Taylor (1948)
"Studies of Human Tolerance for Extreme Heat"
Memo Report No. M.R. MCREXD-696-113A
U.S. Air Force Air Materiel Command
Wright-Patterson Air Force Base, Dayton, Ohio

3. Burch, G.E. (1945)
"Rate of Water and Heat Loss from the Respiratory
Tract of Normal Subjects in Subtropical Climate"
Arch. of Int. Med., vol. 76, p. 315

4. Büttner, K. (1938)
Physikalische Bioklimatology

5. Christie, R.V. and A.L. Loomis (1932)
"The Pressure of Aqueous Vapor in the Alveolar Air"
J. Physiol., vol. 77, p. 35

6. Corlette, C.E. (1942)
"Calculation of Heat and Moisture Dissipated
From the Body by Respiration"
Med. J. of Australia, vol. 2

7. Loewy, A. und H. Gerhartz (1914)
"Über die Temperatur der Expirationsluft
und der Lungen Luft"
Pflüger's Arch., vol. 155, p. 231

8. Moritz, A.R., F.C. Henriques, and McClean (1945)
"Effect of Inhaled Heat Upon Air Passages and Lungs"
Am. J. Path., vol. 21, p. 311

9. Peters, C.C., and W.R. Van Voorhis (1940)
"Statistical Procedures and Their Mathematical Bases"
McGraw-Hill, New York

10. Pfliederer, H. und Lotte Less (1935)
"Die Klimatischen Ansprüche an die Atemwege des menschlichen Körpers"
Bioklim. Zeitschrift, vol. 2, p. 1

11. Seeley, L.E. (1940)
"Study of Changes in the Temperature and Water Vapor Content of Respired Air in the Nasal Cavity"
Tr. Am. Soc. Heat & Vent. Engr., vol. 46, p. 259

12. Taylor, C.L. (1946)
"Human Tolerance for Short Exposures to Heat and Humidity"
Memo Report No. TSEAA-695-56B

13. Walther, J., F.W. Bishop and S.L. Warren
"The Temperature Pattern of Laboratory Animals in Normal and Febrile States"
Temperature (1941) Am. Inst. Physics

APPENDIX

TABLES OF BASIC DATA AND PRINCIPAL CALCULATED QUANTITIES

Guide to Tables

Column:	Datum:
A	Experiment Number
B	Expired Humidity (lb / lb dry air)
C	Inspired Humidity (lb / lb dry air)
D	Water Added by Respiratory Tract (lb / lb dry air)
E	Expired Percent Saturation
F	Inspired Percent Saturation
G	Expired Enthalpy (referred to 98.6°F)
H	Inspired Enthalpy (referred to 98.6°F)
I	Specific Enthalpy Difference (Btu / lb dry air)
J	Temperature and Vapor Pressure Setting (°F) and (in. Hg)
K	Environment Temperature and Vapor Pressure (°F) (in. Hg)
L	Atmospheric Pressure (in. Hg)
M	Duration of Test (min)
N	Respiratory Rate (breaths / min)
O	Respiratory Volume (ft^3 / min)
P	Temperature of Expired Air (°F)
Q	Wet Bulb Temperature of Inspired Air (°F)

APPENDIX

SUBJECT E.R.H.

A	B	C	D	E	F	G	H	I
H-1	0.02830	0.00440	0.02390	88.88	29.55	27.37	-2.74	-30.11
H-2	0.02920	0.00440	0.02480	89.02	29.77	28.50	-2.79	-31.32
H-3	0.03277	0.00979	0.02298	94.22	41.19	32.64	6.11	-26.53
H-4	0.03160	0.00908	0.02252	92.07	38.46	31.42	5.33	-26.09
H-5	0.03341	0.00473	0.02868	94.81	6.07	33.37	9.80	-23.57
H-6	0.03571	0.01488	0.02083	94.67	20.02	36.36	20.06	-16.31
H-7	0.03791	0.02681	0.01110	98.57	29.68	38.83	34.11	- 4.72
H-8	0.03337	0.00414	0.02923	85.92	1.44	34.65	18.95	-15.70
H-9	0.03737	0.01724	0.02013	94.06	7.19	38.40	31.59	- 6.81
H-10	0.03876	0.02685	0.01191	87.16	8.26	40.83	43.99	+ 3.16
H-11	0.03916	0.02573	0.01343	90.04	8.57	41.08	42.25	+ 1.17
H-12	0.03553	0.00823	0.02730	92.96	1.25	36.17	28.45	- 7.72
H-13	0.03767	0.02020	0.01747	90.05	1.92	39.24	43.61	+ 4.37
H-14	0.03935	0.02296	0.01639	93.14	3.45	41.08	44.32	+ 3.24

A	J	K	L	M	N	O	P	Q
H-1	Room Air	68.4 - 0.21	29.80	5.72	7.3	0.178	90.8	51.8
H-2	Room Air	68.2 - 0.21	29.80	5.45	7.9	0.187	91.7	51.6
H-3	Room Air	82.0 - 0.47	29.70	5.60	6.3	0.174	93.5	65.6
H-4	Room Air	81.8 - 0.43	29.70	4.13	6.8	0.240	93.1	64.7
H-5	120 - 0.39	118.8 - 0.35	29.73	5.90	5.3	0.168	93.9	70.2
H-6	120 - 0.79	117.3 - 0.70	29.63	5.40	5.4	0.185	96.0	81.5
H-7	120 - 1.18	123.5 - 1.24	29.70	6.68	5.7	0.151	96.6	92.8
H-8	160 - 0.39	159.2 - 0.31	29.73	5.30	6.0	0.192	96.9	80.6
H-9	160 - 0.79	153.9 - 0.82	29.72	5.25	5.9	0.195	97.6	91.1
H-10	160 - 1.18	162.6 - 1.24	29.80	4.44	6.5	0.237	101.1	99.2
H-11	160 - 1.18	160.4 - 1.19	29.72	5.73	5.4	0.183	100.4	98.4
H-12	200 - 0.39	180.3 - 0.39	29.73	5.35	5.2	0.195	96.4	88.5
H-13	200 - 0.79	189.5 - 0.94	29.72	7.10	4.7	0.145	99.2	99.1
H-14	200 - 1.18	180.5 - 1.07	29.73	7.38	4.2	0.144	99.5	99.6

APPENDIX

SUBJECT W.V.B.

A	B	C	D	E	F	G	H	I
B-1	0.02905	0.00349	0.02556	87.71	21.87	28.45	-3.19	-31.64
B-2	0.02977	0.00364	0.02613	88.42	22.24	29.46	-2.86	-32.32
B-3	0.03333	0.01100	0.02233	100.00	35.11	32.61	9.39	-23.22
B-4	0.03456	0.01096	0.02360	100.00	34.98	34.16	9.35	-24.81
B-5	0.03461	0.00467	0.02994	94.77	5.68	35.07	10.16	-24.91
B-6	0.03541	0.01664	0.01877	94.78	21.36	35.97	22.27	-13.70
B-7	0.03658	0.02460	0.01198	95.41	30.01	37.00	31.00	- 6.00
B-8	0.03601	0.01403	0.02198	89.78	5.33	37.13	28.84	- 8.29
B-9	0.03902	0.02089	0.01813	98.21	7.78	40.24	36.28	- 3.96
B-10	0.03768	0.02613	0.01155	85.27	8.43	39.54	42.90	+ 3.36
B-11	0.04035	0.02780	0.01255	96.46	10.35	42.18	45.64	+ 1.46
B-12	0.03848	0.01148	0.02700	91.08	1.16	40.09	33.93	- 6.16
B-13	0.03859	0 01971	0.01888	88.45	2.24	40.29	42.25	+ 1.96
B-14	0.03954	0.02788	0.01166	90.92	3.16	41.38	51.08	+ 9.70

A	J	K	L	M	N	O	P	Q
B-1	Room Air	70.4 - 0.17	29.78	5.90	6.4	0.176	92.0	51.0
B-2	Room Air	71.1 - 0.17	29.78	5.53	6.7	0.192	92.5	51.6
B-3	Room Air	90.3 - 0.52	29.66	4.95	7.9	0.192	92.0	69.9
B-4	Room Air	90.3 - 0.52	29.66	5.40	8.3	0.177	93.0	69.8
B-5	120 - 0.39	120.5 - 0.35	29.66	4.55	8.4	0.215	95.0	70.7
B-6	120 - 0.79	118.8 - 0.78	29.71	4.19	6.7	0.254	95.7	83.4
B-7	120 - 1.18	120.4 - 1.14	29.71	4.77	6.1	0.212	96.5	90.6
B-8	160 - 0.39	156.6 - 0.66	29.66	5.08	6.3	0.201	97.9	89.0
B-9	160 - 0.79	157.2 - 0.97	29.66	5.00	7.0	0.192	97.6	94.5
B-10	160 - 1.18	161.3 - 1.20	29.80	4.46	6.7	0.237	100.9	98.7
B-11	160 - 1.18	157.2 - 1.28	29.66	4.82	7.5	0.205	99.2	99.1
B-12	200 - 0.39	188.4 - 0.54	29.65	4.95	6.9	0.212	99.5	93.5
B-13	200 - 0.79	186.2 - 0.92	29.65	5.40	7.2	0.192	100.5	98.2
B-14	200 - 1.18	186.3 - 1.28	29.63	5.40	6.7	0.199	100.4	103.4

APPENDIX

[illegible]

A	B	C	D	E	F	G	H	I
M-1	0.02972	0.00760	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
M-2	0.03021	0.00383	[illegible]	87.72	[illegible]	30.44	[illegible]	[illegible]
M-3	0.03096	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.72	-14.66
M-4	[illegible]	0.01724	[illegible]	[illegible]	[illegible]	34.47	[illegible]	[illegible]
M-5	0.03682	0.02378	[illegible]	[illegible]	[illegible]	37.41	[illegible]	[illegible]
M-6	[illegible]	0.00605	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
M-7	0.03476	[illegible]	[illegible]	[illegible]	6.80	[illegible]	[illegible]	[illegible]
M-8	[illegible]	[illegible]	[illegible]	[illegible]	11.25	[illegible]	[illegible]	[illegible]
M-9	[illegible]	[illegible]	[illegible]	[illegible]	0.13	[illegible]	[illegible]	[illegible]
M-10	[illegible]	[illegible]	[illegible]	84.12	[illegible]	[illegible]	[illegible]	[illegible]
M-11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

A	J	K	L	M	N	O	P	Q
M-1	Room Air	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
M-2	Room Air	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
M-3	120 - 0.39	116.9 - 0.11	29.87	[illegible]	[illegible]	[illegible]	[illegible]	66.2
M-4	120 - 0.79	116.7 - [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
M-5	120 - 1.18	117.6 - 1.10	[illegible]	4.45	[illegible]	0.210	95.6	89.5
M-6	160 - 0.39	155.6 - 0.29	29.72	5.40	11.9	0.189	98.4	81.4
M-7	160 - 0.79	156.4 - 0.72	29.72	5.25	11.6	0.190	98.0	89.8
M-8	160 - 1.18	157.1 - 1.41	29.72	5.20	9.8	0.190	99.1	100.6
M-9	200 - 0.39	197.3 - 0.11	29.87	6.30	11.1	0.153	98.5	86.9
M-10	200 - 0.79	194.1 - 0.93	29.75	6.75	11.0	0.139	100.8	100.0
M-11	200 - 1.18	193.6 - 1.17	29.75	5.44	12.5	0.184	100.1	102.8

APPENDIX

SUBJECT L.D.

A	B	C	D	E	F	G	H	I
D-1	0.02841	0.00378	0.02463	88.07	25.06	27.60	-3.28	-30.88
D-2	0.02852	0.00381	0.02471	88.11	24.23	27.72	-2.96	-30.68
D-3	0.03058	0.00214	0.02844	84.55	2.84	30.73	6.82	-23.91
D-4	0.03233	0.01545	0.01688	91.46	19.89	32.37	21.00	-11.37
D-5	0.03501	0.02630	0.00871	91.31	33.55	35.80	32.44	- 3.36
D-6	0.03260	0.00173	0.03087	78.18	0.56	33.90	16.90	-17.00
D-7	0.03490	0.01598	0.01892	83.97	4.49	36.27	33.02	- 3.25
D-8	0.03522	0.02500	0.01022	80.72	7.37	37.00	42.32	+ 5.32
D-9	0.03436	0.00175	0.03261	78.75	0.12	36.05	25.00	-11.05
D-10	0.03530	0.01602	0.01928	82.50	1.18	36.91	40.11	+ 3.20
D-11	0.03644	0.02517	0.01127	82.20	1.54	38.65	50.64	+11.99

A	J	K	L	M	N	O	P	Q
D-1	Room Air	68.8 - 0.18	29.80	1.54	23.4	0.677	91.2	50.8
D-2	Room Air	70.0 - 0.18	29.80	2.30	22.6	0.455	91.3	51.4
D-3	120 - 0.39	117.7 - 0.10	29.87	2.98	19.1	0.340	94.7	66.4
D-4	120 - 0.79	118.7 - 0.72	29.82	3.72	18.3	0.287	94.0	82.2
D-5	120 - 1.18	119.0 - 1.14	29.82	3.85	16.4	0.254	96.5	91.9
D-6	160 - 0.39	161.3 - 0.08	29.86	3.06	18.6	0.340	99.1	78.1
D-7	160 - 0.79	165.1 - 0.75	29.79	3.48	14.7	0.293	99.0	92.0
D-8	160 - 1.18	163.8 - 1.16	29.79	2.74	21.5	0.361	100.5	98.3
D-9	200 - 0.39	194.9 - 0.08	29.86	2.82	21.3	0.375	100.5	85.8
D-10	200 - 0.79	193.6 - 0.75	29.82	2.96	19.3	0.340	99.9	97.1
D-11	200 - 1.18	196.2 - 1.17	29.82	3.10	19.0	0.333	101.0	103.2

APPENDIX

SUBJECT G.L.T.

A	B	C	D	E	F	G	H	I
T-1	0.02805	0.00374	0.02431	87.79	25.64	26.90	-3.56	-30.46
T-2	0.02899	0.00386	0.02513	89.99	26.36	27.99	-3.41	-31.40
T-3	0.03082	0.00214	0.02868	87.19	2.99	30.81	6.42	-24.79
T-4	0.03301	0.01511	0.01790	94.61	21.11	32.98	20.00	-12.98
T-5	0.03443	0.02661	0.00782	93.66	34.05	34.86	32.73	- 2.13
T-6	0.03181	0.00164	0.03017	75.79	0.56	32.15	16.45	-15.70
T-7	0.03147	0.01529	0.01618	75.23	4.44	32.77	32.06	- 0.71
T-8	0.03310	0.02395	0.00915	76.36	7.70	34.74	40.60	+ 5.86
T-9	0.03403	0.00179	0.03224	74.58	0.11	36.09	25.36	-10.73
T-10	0.03378	0.01576	0.01802	77.42	0.83	34.79	40.94	+ 6.15
T-11	0.03579	0.02554	0.01025	81.25	1.57	37.77	51.02	+13.25

A	J	K	L	M	N	O	P	Q
T-1	Room Air	67.8 - 0.18	29.80	3.70	13.2	0.286	90.9	50.2
T-2	Room Air	67.9 - 0.19	29.80	4.10	13.9	0.261	91.2	50.5
T-3	120 - 0.39	116.0 - 0.10	29.87	4.32	13.0	0.222	94.0	65.8
T-4	120 - 0.79	116.1 - 0.70	29.82	5.67	11.1	0.189	93.6	81.3
T-5	120 - 1.18	118.9 - 1.23	29.82	4.15	14.5	0.242	95.2	92.0
T-6	160 - 0.39	159.8 - 0.08	29.86	4.34	14.1	0.233	99.3	77.4
T-7	160 - 0.79	164.2 - 0.72	29.79	4.75	14.7	0.214	99.2	91.3
T-8	160 - 1.18	161.4 . 1.11	29.79	4.52	13.9	0.221	100.3	97.1
T-9	200 - 0.39	196.2 - 0.09	29.86	4.60	12.8	0.231	101.9	86.0
T-10	200 - 0.79	198.1 - 0.74	29.82	4.05	15.1	0.249	100.5	97.4
T-11	200 - 1.18	196.1 - 1.18	29.82	4.02	13.4	0.270	100.8	103.3